

Application and potential timelines for quantum computing in earth system modelling

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The quantum computing opportunity

Aimed at problems that scale beyond the reach of classical systems.

Simulation

Represent molecules, materials and reactions natively, where classical memory grows exponentially.

Improved accuracy through better representation of natural systems

Optimisation

Process vast combinatorial spaces: scheduling, network design, parameter tuning.

Altered computational resource profiles leading to lower power (and CO₂) footprints (*)

AI / Machine learning

Quantum distributions applied to generative AI models.

New model classes and sampling methods for complex, high-dimensional distributions

TODAY

Many modalities being pursued
Broad state of development and readiness
First benefits being demonstrated

~2029–2031

Roadmaps target hundreds to 1,000+ qumodes and logical qubits

MID-TO-LATE 2030S

Production-level, fault-tolerant systems likely
Economics matter greatly

Where earth system models strain

Resolution vs. cost

Km-scale global grids and long runs strain exascale machines; halving grid spacing costs ~10× more compute.

Unresolved processes

Clouds, convection and turbulence fall below the grid and are parameterised, a leading source of projection spread.

Chaos and uncertainty

Sensitivity to initial conditions demands large ensembles to quantify risk, multiplying the cost of every run.

Biogeochemistry

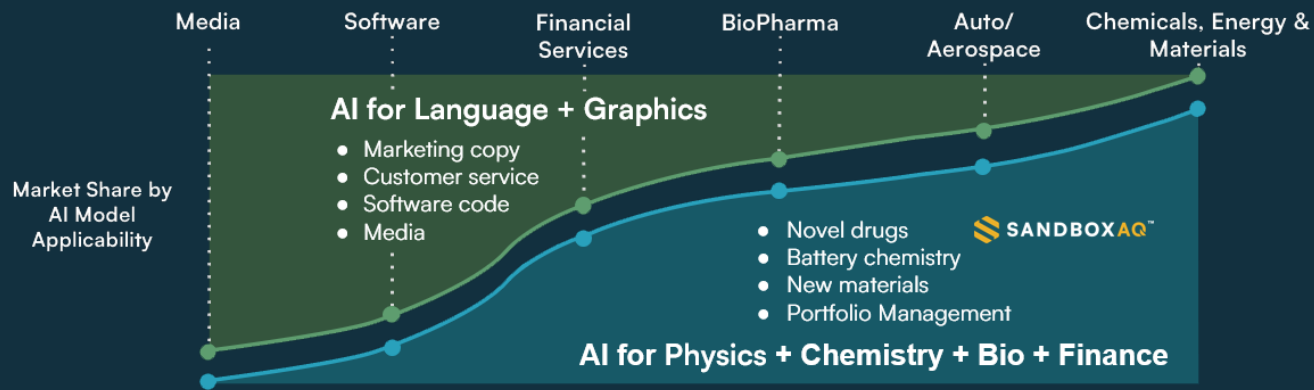
Carbon, nitrogen and aerosol cycles hinge on molecular processes that are poorly constrained and costly to simulate.

THE ROLE OF AI

AI is already impacting the field

- ML weather models used in conjunction with physics-based models
- Limits remain including data hunger, extrapolation to unseen climates, physical consistency

Broader adoption of Large Quantitative Models



Every classical computing approach has significant sustainability and economic challenges

Where quantum could apply, and when

NOW – ~2029

Augmenting AI models

- Quantum distributions for generative ensembles
- Hybrid physics informed neural networks for aerosol modelling
- Hybrid quantum-classical ML for emulators and downscaling
- Hybrid satellite imagery super-resolution
- Small to medium scale optimisation tasks, e.g. sensor placement

~2030 – 2035

Early fault tolerance

- Quantum chemistry for biogeochemical and aerosol processes
- Better-constrained inputs for parameterisations
- Larger optimisation problems

MID-TO-LATE 2030s +

Production-scale systems systems

- Quantum algorithms for nonlinear dynamics: turbulence, cloud formation
- Components embedded in hybrid HPC-quantum models
- Open question: data loading and readout costs

Near-term, quantum's most realistic role is augmenting AI-driven earth system modelling, not replacing it – with potential for energy and cost benefits

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